Enhanced Condensation for Organic Rankine Cycle

6th Quarterly Progress Report

Reporting Period: April 1, 2014 – June 30, 2014

Project Grantor:	**Alaska Energy Authority** Alan Baldivieso, Program Manager 813 W. Northern Lights Blvd. AK 99503 907-771-3027 (voice), Email: abaldivieso@aidea.org
Project Grantee:	University of Alaska, Institute of the Northern Engineering Maggie Griscavage P.O. Box 757880, Fairbanks, AK 99775 907-474-7301 (voice), Email: fygrcon@uaf.edu\
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Principal Investigators: **Sunwoo Kim**, PhD (PI)
Mechanical Engineering Department
University of Alaska, Fairbanks
907-474-6096 (voice), Email: swkim@alaska.edu

1. Back Ground

Generating electricity from low grade heat sources has attracted attention due to rising fuel price and increasing energy demand. The organic Rankine cycle (ORC) system is the most practical solution among technologies developed for low grade heat recovery. However, the efficiency of a typical small scale ORC is 10% or less. Most energy loss in the ORC is attributed to thermodynamically irreversible heat transfer processes occurring in its heat exchangers: the evaporator and condenser. In particular for waste heat recovery ORCs, economical success is mainly determined by effectiveness of the condenser because, while their heat source is provided at no cost, heat rejection accounts for most of operation cost. Almost half of total cost for operation and maintenance of an ORC system can stem from its condenser. We investigate and demonstrate heterogeneous condensing surfaces that potentially reduce the irreversibility during the condensation of organic fluids.

2. Progress Report

We have made progress during the reporting period (April 1 – Jun 30, 2014) and progress activities are described below.

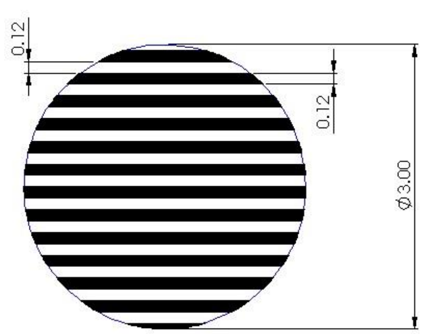
Task 1: Model Development (Completed)

Task 2: Design and Construction of Testing Apparatus (Completed)

The designed condensation testing apparatus has been constructed. Regular maintenance is being continuously conducted. It includes calibration of sensors, replacement of o-rings, reapplication of sealant, and leaking test.

Task 4: Optimization of design parameters

During the reporting period we evaluated the performance of a heterogeneous condensing surface in comparison with the plain copper sample and the fully hydrophobic-treated copper sample. The heterogeneous sample was prepared through machining the hydrophobic samples in such a way that the sample has alternative hydrophobic layers and copper substrate layers, as shown in Fig 1. For removal of the hydrophobic coating layer, a precise milling machine was used. The machine minimum cutting thickness of 25.4 μm was sufficient to clearly mill the coating, showing that the thickness of coating is thinner than the cutting thickness. The dark region stands for the hydrophobic surface and the light region the bare copper. All the dimensions shown in the figure are in inches.



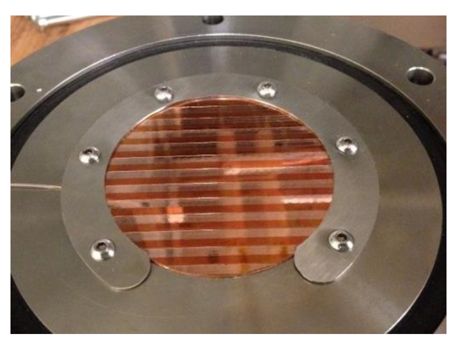


Figure 1: Heterogeneous condensing surface (left: design, right: photograph when it is attached in the condensation apparatus)

Details on the heterogeneous condensing surface sample can be found in the previous report.

This sample was tested with its stripes being horizontal, which means that the stripes are perpendicular to the direction of gravitational acceleration. The angle of the stripes with respect to the gravitational acceleration direction can significantly affect the condensation behavior and thus performance. This is true because of the fact that large drops on the condensation surface begin falling off when the body force due to gravity exceeds the surface tension on the contact area between the droplet and the solid surface. Also, a falling drop sweeps all small drops on its path. The path is in the same direction of gravitational acceleration.

Heat transfer rate per unit area (Heat flux)

Heat transfer rate per unit area (or heat flux) was experimentally determined on the horizontal heterogeneous condensing surface sample. Although the drop size and the coalescence of drops varied on the hydrophobic and hydrophilic stripes, the drop which departed from the top half of the hydrophobic stripe swept away the drops on the hydrophilic stripe. As a result, the drop generation and the rate of drop departure were as good as that of the hydrophobic-treated copper sample. However, in the heterogeneous sample, the drops that were generated on the hydrophilic and hydrophobic stripes on the top half of the sample, which were the first 3-4 stripes, took longer to depart from the surface when compared to other drops on the bottom half of the sample. It took as much as twice to thrice longer than the other drops on the bottom half of the surface. It was really hard to differentiate the drop sizes, since the sweeping away of drops happened so fast.

When the subcooling temperatures (the difference between the vapor saturation temperature and the condensing surface temperature) were smaller than 3℃, the drop generation was in the beginning stage. In other words, drops did not cover the entire condensing surface, exposing the bare surface to the vapor. With an increase in the degree of subcooling, the drop formation increased, leaving no bare condensing surface. The drop generation and rate at which drops depart from the surface were faster than that at smaller subcooling temperatures (< 3℃).

Figure 2 is a graph plotting for the heat transfer rate per unit area (heat flux) at various subcooling temperatures. From the graph it was evident that below subcooling temperature of 3℃ the heat flux for the horizontal heterogeneous surface was nearly identical to the heat flux for the fully hydrophobic-treated copper sample. This may be due to the same bare surface area of the condensing surface in an early stage of condensation. At smaller subcooling temperatures, the bare surface that was exposed to the vapors was same in both cases. As the degree subcooling increased (> 3℃), the drops started to drain away from the surface. The drops from the hydrophobic stripes swept away the drops on the hydrophilic stripes, except for the drops of the first few stripes on the top half that were unable to be swept away. Thus, the resistance offered by the drops that were unable to be swept away came into the picture, resulting in a higher thermal resistance offered by the drops. After the subcooling temperature of 3℃, the heat flux for the horizontal heterogeneous copper sample kept increasing due to more thermal resistance.

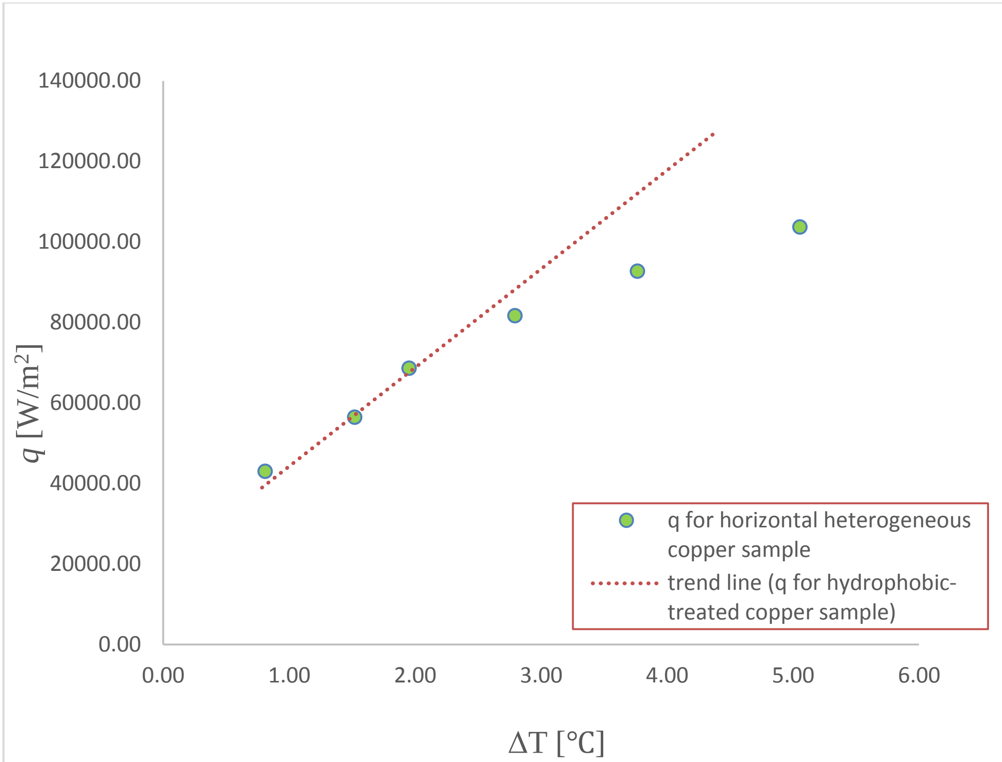


Figure 2: Heat transfer rate per unit area on the horizontal heterogeneous copper sample

Figure 3 is a graph showing the condensation heat transfer coefficient for various subcooling temperature. The condensation heat transfer coefficient was measured higher at smaller subcooling temperatures because the drops generated on the condensing surface did not cover the entire surface. Resulting was bare surface exposure which led to higher heat transfer coefficients at smaller subcooling temperatures (< 3℃). After the subcooling temperatures of 3℃, the steepness of the slope of the curve starts decreasing, indicating that in the change in heat transfer coefficient was less dependent on the rate of condensation. A comparison graph is also shown in the figure between the hydrophobic-treated copper sample and the horizontal heterogeneous sample. Below the subcooling temperatures of 3℃, the heat transfer coefficients for the two samples were almost identical and after the subcooling temperature of 3℃, the heat transfer coefficient started decreasing for the horizontal heterogeneous surface, resulting from the increase in thermal resistance due to the drops which were unable to be swept away on the top half of the sample.

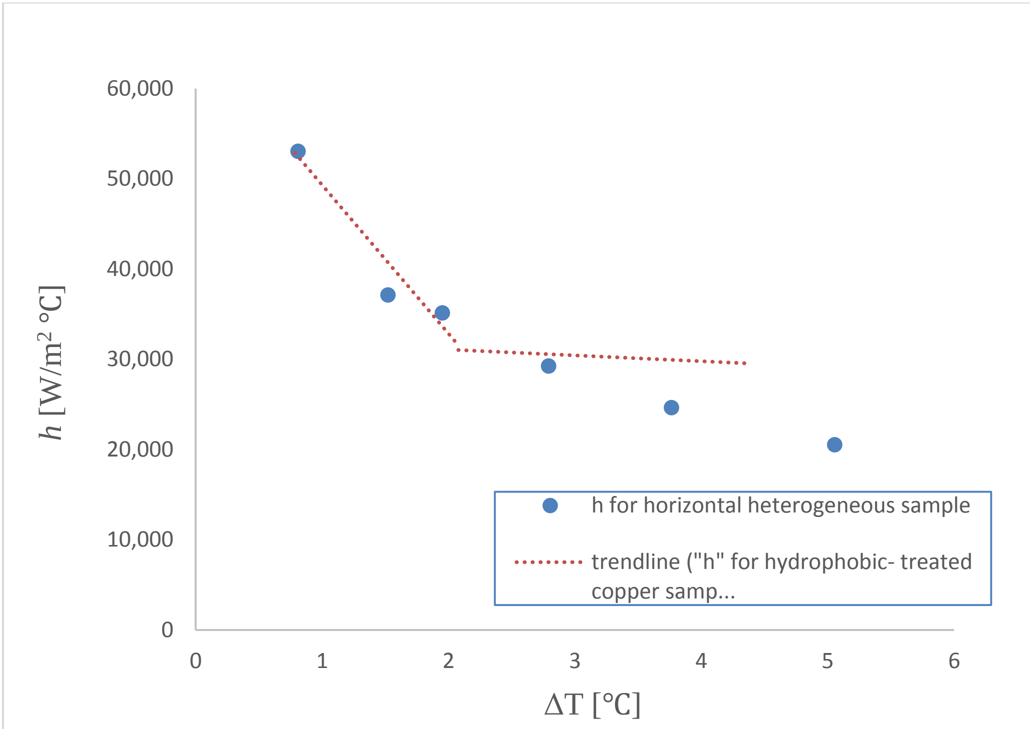


Figure 3: Condensation heat transfer coefficient on the horizontal heterogeneous sample.